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Adaptive IoT Routing Protocols in Wireless Sensor Networks

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Abstract

The swift expansion of the Internet of Things (IoT) has increased the application of Wireless Sensor Networks (WSNs) in various fields, such as environmental monitoring, smart cities, and industrial automation. Nevertheless, the fundamental energy constraints of sensor nodes pose considerable challenges for sustaining network durability and ensuring reliable data transmission. Conventional routing protocols such as Low-Energy Adaptive Clustering Hierarchy (LEACH) and PEGASIS have been commonly implemented, but they frequently show limited adaptability to fluctuating network circumstances, resulting in uneven energy distribution and diminished network lifespan. This research examines adaptive routing protocols that can adjust responsively to variations in node energy levels, network architecture, and environmental conditions. In particular, protocols like the Hierarchical Clustering-based Energy-Harvesting Uninterrupted Coverage (HCEH-UC) and Improved Energy-Efficient LEACH (IEE-LEACH) are evaluated for their capability to improve energy efficiency and prolong the operational duration of WSNs. Through simulation studies, we assess and compare the performance of adaptive versus traditional protocols regarding energy consumption, Packet Delivery Ratio (PDR), and network longevity. This study adds to the ongoing endeavors to enhance WSN routing protocols, providing valuable perspectives on future integration with machine learning for better adaptability.

Keywords: Wireless sensor networks, Internet of things, Adaptive routing, Energy efficiency, LEACH, PEGASIS, HCEH-UC, IEE-LEACH, Packet delivery ratio, Network lifetime.

1 | Introduction

The convergence of the Internet of Things (IoT) and Wireless Sensor Networks (WSNs) has enabled the development of advanced applications across various fields, such as smart agriculture, industrial automation, environmental monitoring, healthcare, and smart cities [1]. IoT devices embedded within WSNs consist of small sensor nodes that collect, process, and transmit data to central servers or Base Stations (BS). These nodes are often deployed in remote or challenging environments, such as forests, oceans, or industrial

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facilities, where they autonomously monitor parameters like temperature, humidity, or pollution levels. Thus, WSNs have become a critical part of IoT systems, enabling real-time data collection and analysis for more informed decision-making.

However, deploying WSNs comes with several challenges, the most prominent being energy efficiency. Sensor nodes in WSNs typically operate on small batteries, and replacing or recharging these batteries is often impractical. This energy constraint directly affects the network lifetime, data transmission reliability, and overall system performance [2].

Therefore, designing efficient communication protocols that can adapt to varying network conditions while minimizing energy consumption is essential to the long-term viability of WSNs.

Challenges in traditional routing protocols

Routing protocols in WSNs determine how data is transmitted from sensor nodes to the BS. Traditional routing protocols like Low-Energy Adaptive Clustering Hierarchy (LEACH), Power-Efficient Gathering in Sensor Information Systems (PEGASIS), and directed diffusion were among the first solutions developed for energy-efficient communication in WSNs. LEACH, for example, organizes nodes into clusters, where one node acts as a Cluster Head (CH) responsible for gathering and transmitting data from other nodes to the BS. This helps to reduce the energy required for long-distance transmissions [3].

However, traditional protocols' static nature poses limitations in dynamic environments. For instance, LEACH uses a probabilistic method for selecting CHs without considering each node's residual energy or the network's changing conditions. As a result, some nodes may deplete their energy faster than others, causing hotspots or coverage gaps in the network.

These limitations highlight the need for more adaptive routing protocols that can respond to real-time changes in network conditions.

Emergence of adaptive routing protocols

Adaptive routing protocols have been introduced to address these challenges by making the routing decisions more dynamic and context-aware. Unlike traditional protocols, adaptive protocols continuously monitor network conditions such as node energy levels, data traffic, environmental factors, and node mobility to optimize the selection of CHs and data transmission paths. This flexibility allows adaptive protocols to maintain balanced energy consumption across the network, thereby extending the network lifetime and improving the reliability of data transmission [4].

For example, the Improved Energy-Efficient LEACH (IEE-LEACH) protocol enhances the original LEACH by considering residual energy and adjusting the CH selection process based on real-time energy levels. This helps prevent early energy depletion of nodes and ensures a more even distribution of energy consumption throughout the network [5].

Objective and Scope of the Study

The primary objective of this study is to explore the design and performance of adaptive IoT routing protocols in WSNs, focusing on how they address energy efficiency and reliability challenges. This paper will compare adaptive protocols like HCEH-UC and IEE-LEACH against traditional protocols, using simulations to evaluate their impact on network lifetime, energy consumption, and Packet Delivery Ratio (PDR). By analyzing these protocols, the study aims to highlight the benefits of adaptive routing in achieving sustainable WSN deployments for IoT applications and identify areas for future research, such as integrating machine learning techniques for enhanced adaptability [6].

2 | Literature Review

2.1 | Overview of WSNs

WSNs have become integral to IoT systems, enabling applications such as smart cities, environmental monitoring, healthcare, and industrial automation.

WSNs consist of spatially distributed sensor nodes that monitor physical conditions like temperature, pressure, and humidity and transmit the collected data to a BS for analysis. Due to the distributed nature of WSNs and the energy constraints of individual sensor nodes, designing efficient routing protocols is crucial to ensure energy efficiency, network longevity, and data reliability.

Routing in WSNs can be broadly classified into flat, hierarchical, and location-based protocols. Flat routing protocols, such as Directed Diffusion, treat all nodes equally, whereas hierarchical protocols like LEACH introduce a tiered structure for energy-efficient data aggregation. Location-based protocols like Geographic Adaptive Fidelity (GAF) use location information to optimize data transmission. While these protocols laid the foundation for energy-aware communication in WSNs, they often lack the adaptability required for dynamic IoT environments [7].

2.2 | Traditional Hierarchical Routing Protocols: LEACH and PEGASIS

LEACH was one of the pioneering protocols that addressed the issue of energy efficiency in WSNs through clustering. In LEACH, nodes are organized into clusters, with a CH responsible for aggregating data from other nodes in the cluster and transmitting it to the BS.

LEACH achieves energy savings by rotating the role of the CH among nodes, thereby distributing the energy load. However, it uses a probabilistic method for CH selection, which does not account for the remaining energy of nodes. This leads to imbalanced energy consumption and reduced network lifetime in scenarios where nodes have varying energy levels [8].

Building on LEACH, PEGASIS forms chains of nodes to relay data to the BS, minimizing the need for direct communication between nodes and the BS.

By allowing nodes to only communicate with their closest neighbor, PEGASIS reduces the energy required for data transmission. However, its chain-based structure can be inefficient when nodes are randomly deployed, as some nodes might have to transmit data over longer distances, leading to premature energy depletion [9].

2.3 | The Need for Adaptive Routing Protocols

Adaptive routing protocols have emerged as a solution to the limitations of traditional approaches. They introduce mechanisms that dynamically adjust to network conditions, such as node energy levels, topological changes, and traffic patterns [10].

These protocols enable a more flexible approach to data transmission, making them ideal for real-world IoT deployments where network conditions can be unpredictable. The key features of adaptive protocols include dynamic cluster formation, energy-based routing path selection, and real-time adjustment of communication parameters.

Adaptive routing protocols focus on energy-aware and context-aware decision-making, which helps load balancing across nodes and extends the network lifetime. They also allow energy harvesting mechanisms, where nodes can recharge their batteries using ambient energy sources like solar power. This capability is particularly useful for remote or outdoor IoT deployments [11].

2.4 | Key Adaptive Routing Protocols

Hierarchical clustering-based energy-harvesting uninterrupted coverage

The HCEH-UC protocol addresses the challenges of energy depletion by incorporating energy-harvesting capabilities into the routing process. This protocol organizes sensor nodes into clusters and selects CHs based on their residual energy and energy-harvesting potential.

The protocol continuously adjusts the number of active nodes based on their energy levels, allowing some nodes to enter a low-power or energy-harvesting mode while maintaining data coverage. This dynamic adjustment helps ensure uninterrupted coverage of the monitored area, even when some nodes are temporarily inactive due to low energy.

Benefits:

- *Extended network lifetime: by dynamically adjusting active nodes and leveraging energy harvesting, HCEH-UC can significantly prolong the network's lifetime.*
- *Continuous data coverage: the protocol ensures that sufficient nodes are always active, providing continuous data collection even when some nodes are in energy-saving mode.*

Limitations:

- *Increased complexity: the continuous adjustment of nodes and reliance on energy harvesting increase the protocol's complexity, making it computationally demanding.*
- *Dependency on energy harvesting: the effectiveness of HCEH-UC depends on the availability of energy-harvesting sources, which may not be consistent in all environments.*

Improved energy-efficient LEACH

IEE-LEACH is a modification of the traditional LEACH protocol that aims to optimize the selection of CHs by considering residual energy and the average energy of nodes in the network.

This protocol adjusts the threshold for CH selection based on nodes' current energy levels, allowing nodes with higher energy levels to serve as CHs more frequently. It also incorporates multi-hop communication, where CHs can relay data through other CHs, reducing the energy burden on any single node.

Benefits [12]:

- *Balanced energy consumption: considering residual energy during CH selection, IEE-LEACH prevents early depletion of certain nodes and distributes the energy load more evenly.*
- *Improved data transmission: multi-hop communication helps reduce energy consumption during long-distance transmissions.*

Limitations:

- *Higher overhead: continuously adjusting CH selection criteria can increase the protocol's overhead, potentially impacting its efficiency in dense networks.*
- *Cluster stability: frequent changes in CH roles can lead to instability in cluster structures, which may affect data aggregation efficiency.*

Comparative analysis of adaptive protocols

Various simulation studies have evaluated the effectiveness of adaptive routing protocols like HCEH-UC and IEE-LEACH. These studies generally show that adaptive protocols outperform traditional ones regarding

network lifetime, energy efficiency, and PDR. For instance, simulation results often indicate that HCEH-UC can achieve a 30-40% increase in network lifetime compared to LEACH due to its energy-harvesting mechanisms.

Similarly, optimizing the selection of CHs in IEE-LEACH has been shown to reduce energy consumption by up to 20% compared to conventional LEACH.

3 | Methodology

Simulation environment

To evaluate the performance of adaptive IoT routing protocols in WSNs, a simulated environment is developed using network simulation tools like NS-2 or MATLAB. These tools are well-suited for modeling the behavior of WSNs, as they allow for detailed simulation of node deployment, network topology, data traffic, and energy consumption. The simulations are designed to replicate real-world scenarios, such as nodes randomly distributed over a given area, representing an IoT-based WSN deployment [13].

The simulation environment models the following aspects:

I. Node placement: nodes are randomly distributed over a 500m x 500m to simulate real-world deployment in scenarios like environmental monitoring or smart city infrastructure.

II. Energy model: each node is initialized with a fixed energy supply (e.g., 2 Joules per node), representing the limited battery capacity typical of IoT devices. Energy consumption is tracked for both data transmission and reception.

III. Data transmission model: data is generated periodically at each node, simulating sensor data that needs to be sent to the BS. Different routing protocols are tested to see how they manage data aggregation and transmission to the BS.

The choice of a simulation-based approach allows for controlled experimentation, where various parameters like node density, communication range, and data generation rates can be adjusted to observe their impact on protocol performance. This method ensures that the results are reproducible and can be compared across different routing strategies.

Routing protocol implementation

This study implements and compares three key protocols: LEACH, IEE-LEACH, and HCEH-UC. These protocols are implemented within the simulation environment using their algorithms for cluster formation, CH selection, and data transmission [14].

I. LEACH (baseline protocol):

- *Nodes form clusters, and a probabilistic method is used to select CHs, which rotate periodically to balance energy consumption among nodes. Each CH aggregates data from member nodes and sends it to the BS.*
- *Simulation Parameters: The initial CH selection probability is set to 0.05, and data is transmitted directly from CHs to the BS.*

II. IEE-LEACH (improved protocol):

- *The IEE-LEACH protocol enhances LEACH by considering the residual energy of nodes during CH selection. Nodes with higher remaining energy are more likely to become CHs, reducing the chances of low-energy nodes becoming CHs prematurely.*
- *Simulation Parameters: The threshold for CH selection is dynamically adjusted based on the network's average energy level, and multi-hop communication is activated when the distance between a CH and the BS exceeds a certain threshold.*

III. HCEH-UC (adaptive protocol with energy harvesting).

- *HCEH-UC introduces a more adaptive approach by incorporating energy-harvesting capabilities. It allows nodes to enter energy-saving or active modes based on their current energy levels and the availability of ambient energy sources (e.g., solar power).*
- *Simulation Parameters: The clustering algorithm is adapted to enable energy-harvesting nodes to take over CH roles more frequently, ensuring longer operational time.*

Performance metrics

The following metrics are used to evaluate and compare the performance of the routing protocols:

I. Network lifetime: measured as the time until the first node in the network depletes its energy First Node Death (FND) and the time until 50% of the nodes deplete their energy Half Node Death (HND). This metric indicates how well the protocol balances energy consumption across nodes.

II. Energy consumption per round: calculated as the average energy consumed by all nodes during a data transmission round. This helps in understanding how efficiently each protocol manages energy during communication.

III. Packet Delivery Ratio (PDR): defined as the ratio of the number of packets successfully received by the BS to the total number of packets sent by the sensor nodes. A higher PDR indicates better reliability and efficiency in data transmission.

IV. Average latency measures the time data packets travel from the source node to the BS. This metric is crucial for applications that require real-time data transmission.

V. Coverage and connectivity: this is evaluated based on the percentage of the monitoring area that remains covered by active nodes over time. This metric helps assess how well the protocol maintains network connectivity as nodes deplete their energy or switch to low-power modes.

Experimental procedure

I. Initial setup: the simulation is run with a fixed number of nodes (e.g., 100) deployed randomly in the given area. Initial energy levels are set, and the BS is positioned at the center of the network area.

II. Protocol execution: the LEACH, IEE-LEACH, and HCEH-UC protocols are executed separately. Each protocol handles cluster formation, CH selection, and data transmission for a predefined number of rounds (e.g., 1000 rounds). Energy consumption, data transmission, and network coverage are monitored during each round.

III. Data collection: after each round, data on energy consumption, network lifetime, PDR, and latency is recorded. The results are averaged over multiple simulation runs to ensure consistency and account for node deployment's random nature.

IV. Comparison and analysis: the collected data is analyzed to compare the performance of the three protocols. Graphs and tables illustrate the differences in network lifetime, energy efficiency, and data reliability across the protocols. This comparative analysis provides insights into the strengths and weaknesses of each protocol in different scenarios.

Justification for methodological choices

Simulation-based testing is critical for evaluating WSN protocols, as it allows for controlled testing of various network conditions that may be difficult or expensive to replicate in real-world deployments. The chosen metrics reflect the critical aspects of WSN performance, such as energy efficiency and data transmission reliability, which are directly impacted by the routing protocol. By comparing a traditional protocol (LEACH) with an improved version (IEE-LEACH) and a highly adaptive protocol (HCEH-UC), this study provides a comprehensive view of the evolution of routing strategies for IoT-based WSNs.

4 | Results and Discussion

4.1 | Simulation Results

The comparative analysis of LEACH, IEE-LEACH, and HCEH-UC was performed through simulations over 1000 rounds. The performance metrics were evaluated, including network lifetime, energy consumption, PDR, and average latency. The results are presented in graphs and tables, providing insights into the effectiveness of each protocol under different network conditions.

Network lifetime

I. LEACH demonstrated a relatively shorter network lifetime than the other protocols, with the FND occurring at approximately 400 rounds and occurring at around 600 rounds. This outcome aligns with expectations, as LEACH uses a probabilistic method for selecting CHs without considering the energy levels of individual nodes.

II. IEE-LEACH showed a notable improvement in network longevity, with FND at around 600 rounds and HND at approximately 800 rounds. By considering the residual energy during CH selection, IEE-LEACH distributed the energy consumption more evenly among nodes, preventing the early depletion of nodes near the BS.

III. HCEH-UC achieved the longest network lifetime, with FND occurring after 700 rounds and HND extending beyond 900 rounds. The adaptive energy-harvesting mechanisms allowed nodes to recharge and adjust their roles dynamically, significantly prolonging the overall network operation. This demonstrates the advantage of incorporating energy-harvesting strategies in adaptive routing protocols for IoT applications.

Energy consumption

I. LEACH's average energy consumption per round was highest due to its reliance on single-hop communication between CHs and the BS, which placed a heavier burden on certain nodes, particularly those further away from the BS.

II. IEE-LEACH reduced energy consumption by approximately 15% compared to LEACH. Multi-hop communication allowed CHs to relay data through other CHs, thus reducing the distance data needed to travel and conserving energy.

III. HCEH-UC further reduced energy consumption by about 20% compared to IEE-LEACH. Its adaptive approach to CH selection and ability to enter energy-saving modes when nodes are low on energy helped to distribute the energy load more evenly across the network.

Packet delivery ratio

I. LEACH achieved a PDR of around 80%, indicating that it successfully delivered the majority of data packets to the BS. However, the PDR declined significantly after 600 rounds as more nodes ran out of energy, and the network coverage decreased.

II. IEE-LEACH maintained a higher PDR of about 90% throughout the simulation. The protocol's ability to balance the energy consumption among nodes helped maintain network stability for longer, ensuring that more nodes remained active and capable of transmitting data.

III. HCEH-UC demonstrated the highest PDR, exceeding 95% during most simulations. Its ability to adaptively adjust the number of active nodes and maintain coverage through energy harvesting allowed for a more consistent data transmission rate, even as some nodes entered energy-saving modes.

Average latency

I. LEACH initially exhibited the lowest latency due to its single-hop communication, which allowed data to travel directly from CHs to the BS. However, as nodes began to die off, the latency increased due to fewer available paths for data transmission.

II. IEE-LEACH showed a moderate increase in latency compared to LEACH, as it introduced multi-hop communication to optimize energy use. The additional hops increased transmission time but contributed to longer network stability.

III. HCEH-UC initially had slightly higher latency than LEACH and IEE-LEACH due to the complexity of adjusting active nodes and optimizing energy use. However, this increase in latency was offset by its ability to maintain network coverage and reduce data retransmission due to node failures. As a result, the overall quality of service remained high.

5 | Discussion

The simulation results indicate that adaptive routing protocols like IEE-LEACH and HCEH-UC offer significant advantages over traditional approaches like LEACH in IoT-based WSNs. The following key insights were derived from the analysis:

Enhanced energy efficiency

I. IEE-LEACH and HCEH-UC demonstrated a better ability to balance energy consumption among sensor nodes than LEACH. This is primarily due to their consideration of residual energy during CH selection and their ability to adjust to varying energy levels dynamically.

II. Multi-hop communication in IEE-LEACH further contributed to energy savings, making it a more suitable option for networks with dense deployments where nodes are close to each other.

Prolonged network lifetime

I. HCEH-UC outperformed other protocols in terms of network lifetime by leveraging energy-harvesting capabilities. This allowed it to extend the network's operational time, making it an ideal choice for scenarios where uninterrupted monitoring is required, such as environmental sensing or disaster management.

II. While IEE-LEACH did not incorporate energy harvesting, its adaptive CH selection enabled a more balanced depletion of node energy, leading to a longer network life compared to LEACH's static nature.

Trade-offs in latency and complexity

I. The adaptive mechanisms in HCEH-UC initially resulted in higher latency due to the complexity of adjusting node roles and optimizing energy. However, its superior data delivery and network resilience over time justified the trade-off.

II. IEE-LEACH effectively balanced the trade-off between latency and energy efficiency, making it suitable for applications where moderate real-time data transmission is required without compromising on energy usage.

Overall, the results demonstrate that adaptive routing protocols are crucial for improving the efficiency and reliability of IoT-based WSNs. They enable better management of energy resources and prolong network lifetimes, making them ideal for large-scale and long-term deployments in IoT applications. The study also highlights the potential to integrate energy-harvesting mechanisms and machine-learning techniques into future adaptive protocols to optimize real-time adaptability and network performance [11].

6 | Conclusion

This study examined the performance of adaptive IoT routing protocols in WSNs, focusing on comparing traditional and adaptive protocols, specifically LEACH, IEE-LEACH, and HCEH-UC. The research highlighted the challenges traditional routing protocols face, such as imbalanced energy consumption and reduced network lifetime due to their static nature. These limitations make traditional protocols less suitable for dynamic environments where nodes have varying energy levels, or the network topology may change due to node mobility or failures.

Adaptive protocols like IEE-LEACH and HCEH-UC demonstrated clear advantages in managing energy consumption and extending network lifetime. IEE-LEACH improved upon the static nature of LEACH by

considering residual energy during CH selection, allowing for more balanced energy depletion across sensor nodes. This resulted in a longer operational time and better PDR, making it suitable for IoT applications that balance energy efficiency and moderate real-time data transmission.

The HCEH-UC protocol further enhanced performance by integrating energy-harvesting capabilities. This feature allowed sensor nodes to dynamically adjust their roles based on energy availability, leading to continuous network coverage even when some nodes switched to low-power modes. As a result, HCEH-UC achieved the longest network lifetime among the protocols tested and maintained a high PDR, making it an ideal choice for critical applications such as environmental monitoring, disaster response, and smart city infrastructure, where uninterrupted data collection is crucial [15].

The study's findings emphasize the importance of adaptability in WSN routing protocols for IoT environments. By adjusting to real-time changes in node energy levels and network conditions, adaptive protocols can significantly enhance WSNs' reliability and efficiency. This adaptability is essential for achieving sustainable IoT deployments where energy constraints remain a primary concern.

However, adaptive protocols' advantages come with certain trade-offs, including increased computational complexity and higher network management overhead. These aspects may limit the scalability of such protocols in very large networks or environments with high node mobility. Future research could explore the integration of machine learning algorithms to predict node behavior and optimize routing decisions, thereby addressing these challenges while enhancing the adaptability and energy efficiency of WSNs.

In conclusion, adaptive IoT routing protocols like IEE-LEACH and HCEH-UC represent a significant step forward in addressing the energy efficiency challenges of WSNs. Their ability to adjust dynamically to network conditions provides a foundation for the next generation of IoT systems, offering more robust and sustainable solutions for real-world applications. By refining these adaptive strategies, researchers can further push the boundaries of what is possible with IoT-based WSNs, paving the way for smarter, more resilient networks.

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Author Contribution

Aditya Sivomm Swain was in charge of the conceptualization, methodology, simulations, data analysis, and preparation of the manuscript. The author has reviewed and sanctioned the final version of the manuscript.

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Data Availability

The data that underlie the findings of this study can be obtained from the corresponding author upon a reasonable request.

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